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# Humidity Calculations Used for Mobile Source Emission Testing

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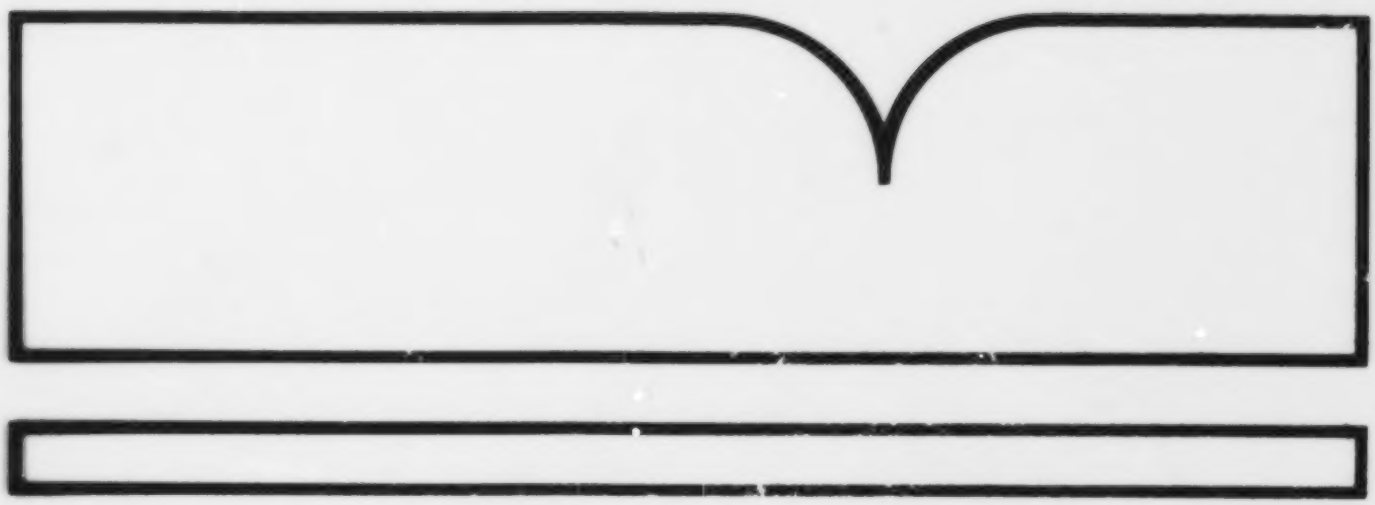

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Technical Report

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# Humidity Calculations Used for Mobile Source Emission Testing


## Abstract

**This reference document provides a summary of the calculations used to determine relative and specific humidity of moisture in air for mobile source (motor vehicle and engine) emission and fuel economy testing at the U.S. Environmental Protection Agency Motor Vehicle Emissions Laboratory in Ann Arbor, Michigan. The reference includes calculations required to determine the saturation vapor pressure of water, psychrometric equations used to calculate the partial pressure of water vapor for wet-bulb psychrometers, and equations for the enhancement factor of water and ice. Described are the methods used from 1971 to 1983.**


Purpose. This reference provides a description of the procedures used to calculate humidity at the EPA Motor Vehicle Emissions Laboratory (MVEL). Several procedures have been used at MVEL for different applications. For heavy duty engine certification between 1979 and 1983, the humidity calculation procedure was defined in the Federal Register; for light duty motor vehicles, the procedure was determined by the testing laboratory from technical and operational considerations, as well as the state of the art of humidity measurement. Manufacturers, EPA contractors, and EPA employees often need to know what procedure is, has been, or, in some instances, should be used to calculate humidity. This reference provides a single document that describes the procedures used historically at MVEL, plus information about procedures that have not been used, but which may be useful in the future.

Overview. Humidity measurement is required for three different calculations used in the analysis of mobile source emission and fuel economy: (1) to correct the measurement of oxides of nitrogen for the effect of moisture in engine intake air, (2) to correct the measurement of carbon monoxide (CO) when water is extracted from exhaust gases, and (3) to convert heavy duty engine emissions from a dry to a wet basis.

The humidity of water in air has an effect on the measurement of oxides of nitrogen. As a result of a study made for EPA by Scott Research Laboratories Inc. in 1970[1], EPA test procedures correct the measurement of oxides of nitrogen for the specific humidity of water in air. Several different correction equations have been used historically to correct oxides of nitrogen for humidity. These can be found in various editions of the Federal Register and are not described here; however, all of these equations required the

measurement of specific humidity in units of grains of water per pound of dry air, grams of water per gram of dry air, or grams of water per kilogram of dry air.

The measurement of percent relative humidity is required for analysis of carbon monoxide (CO) whenever water vapor is extracted from exhaust gas to prevent interference in CO analyzers. The carbon monoxide analyzers used at the EPA laboratory in Ann Arbor are essentially free of interference from water vapor, and for this reason, CO measurements at MVEL are no longer corrected for relative humidity; however, the correction is applied at other testing facilities that use equipment susceptible to interference.

Emission measurements for 1979-1983 model-year engines must be converted from a dry to a wet basis. The calculation used to perform the conversion includes a term for the water-vapor volume concentration, on a dry basis, of the engine intake air. The water-vapor volume concentration equals the specific humidity of the engine intake air multiplied by a constant.

Many methods exist for measuring humidity and are classified as primary and secondary. Secondary methods must be calibrated by means of a primary method and are not ordinarily used for emission testing because most secondary methods lack sufficient accuracy. Primary methods are used that provide good accuracy, are relatively easy and economical to use, and are capable of providing a repeated (or continuous) humidity measurement. Two instruments that satisfy these requirements, and are used for most emission testing, are the dew-point hygrometer and the wet-bulb psychrometer.

Dew-point hygrometers and wet-bulb psychrometers both have acceptable accuracy, when properly calibrated and optimized, and are capable of continuously measuring humidity. In the past, the wet-bulb psychrometer was the most common instrument in use because it was easier and cheaper to use than the hygrometer. The dew-point hygrometer has always had the advantage of superior accuracy.

Within the last ten years, improvements in the design of the dew-point hygrometer have produced an instrument that is easier to use for emission testing than the wet-bulb psychrometer and has superior reliability, as well as better accuracy. The dew-point hygrometer is still more expensive than the wet-bulb psychrometer; however, steady cost reduction, plus the operational superiority of the hygrometer, are rapidly making it the preferred instrument for humidity measurement.

Humidity measurements. Three measurements are required to measure relative and specific humidity: barometric pressure, ambient (dry-bulb) temperature, and either wet-bulb temperature, dew-point temperature, or for temperatures below freezing, ice-point temperature. From these measurements, several intermediate calculations are performed. First, it is necessary to calculate the saturation vapor pressure of water at each temperature; several different equations have been used for this at MVEL. Second, it is necessary to calculate the partial pressure of water vapor. For a dew-point hygrometer this is a trivial calculation; however for the wet-bulb psychrometer a special equation, the psychrometric equation, is required. Relative and specific humidity are then directly calculated from these values. Each of these calculations is described in detail below.

Experimental variables. All of these methods are similar and require the measurement of barometric pressure, ambient temperature, and either dew-point (ice-point) temperature measured with a dew-point hygrometer or wet-bulb temperature measured with a wet-bulb psychrometer. In this article, the following symbols are used to represent values of each measured variable for different units of temperature and pressure.

Tamb(K) = ambient temperature -- degrees Kelvin.
Tamb(C) = ambient temperature -- degrees Celsius.
Tamb(F) = ambient temperature -- degrees Fahrenheit.

Twet(K) = wet-bulb temperature -- degrees Kelvin.
Twet(C) = wet-bulb temperature -- degrees Celsius.
Twet(F) = wet-bulb temperature -- degrees Fahrenheit.

Tdew(K) = dew-point temperature -- degrees Kelvin.
Tdew(C) = dew-point temperature -- degrees Celsius.
Tdew(F) = dew-point temperature -- degrees Fahrenheit.

Tice(K) = ice-point temperature -- degrees Kelvin.

Pbaro = barometric pressure -- same pressure units as saturation vapor pressure.

Many of the equations presented in this article are pressure unit independent; that is, the equation is valid for any pressure unit as long as all pressures are expressed in the same units, and as long as the pressure of a perfect vacuum is defined to equal zero.

Saturation vapor pressure. Ambient temperature and either dew-point, ice-point, or wet-bulb temperature are measured experimentally - and the saturation vapor pressure of water (or ice) is calculated at each temperature. The following variables are used to represent saturation vapor pressure at different temperatures and pressures:

Pamb(Pa) = the saturation vapor pressure at the ambient temperature -- Pascals.

Pamb(InHg) = the saturation vapor pressure at the ambient temperature -- inches of mercury.

Pwet(Pa) = the saturation vapor pressure at the wet-bulb temperature -- Pascals.

Pwet(InHg) = the saturation vapor pressure at the wet-bulb temperature -- inches of mercury.

Pdew(Pa) = the saturation vapor pressure at the dew-point temperature -- Pascals.

Pdew(InHg) = the saturation vapor pressure at the dew-point temperature -- inches of mercury.

Pice(Pa) = the saturation vapor pressure at the ice-point temperature -- Pascals.

Historically, MVEL has used four different equations to calculate saturation vapor pressure. The actual difference between equations is not large and the effect of differences is much less significant than other sources of error in vehicle emission testing.

The oldest equation used at MVEL is formula 2 of Smith, Keyes, and Gerry[3], equation (1) below, which has been used for light duty vehicle testing to the present date (1983). Equation (1) determines saturation vapor pressure Psat (inches of mercury) at temperature T(K) (degrees Kelvin ITS-26). Pamb(InHg), Pdew(InHg), or Pwet(InHg) can be determined by substituting Tamb(K), Tdew(K), or Twet(K) for T(K) in equation (1):

$$Psat(InHg) = 29.92\ Pc\ 10^{-[X / T(K)]\ [A + B X + C X^{3}] / [1 + D X]} \quad (1)$$

where
- Tc = 647.27
- Pc = 218.167
- A = 3.2437814
- B = 5.86826E-3
- C = 1.1702379E-8
- D = 2.1878462E-3
- T(K) = .5555 [ T(F) - 32 ] + 273.16
- X = Tc - T(K)
- T(F) = temperature degrees Fahrenheit.

Formula 2 of Smith, Keyes, and Gerry is valid for a temperature range of 10 to 150 degrees Celsius.

In 1947 the Goff-Gratch formulation for the saturation vapor pressure of water over water and ice, which is not presented here, was adopted for international use in Resolution 164 of the Twelfth Conference of Directors of the International Meteorological Organization'. The Goff-Gratch formulation, which is still used in meteorology, was used at the U.S. National Bureau of Standards until 1971, when the NBS developed a new equation. The 1971 NBS equation, equation 23 of Wexler and Greenspan, is the second equation used at MVEL'. This equation, (2) below, has been used for heavy duty engine testing from 1979 to 1983. Equation (2) determines saturation vapor pressure Psat (Pascals) at temperature T(K) (degrees Kelvin IPTS-68). Pamb(Pa), Pdew(Pa), or Pwet(Pa) can be determined by substituting Tamb(K), Tdew(K), or Twet(K) for T(K) in equation (2):

$$Psat(Pa) = \exp\left( B \ln T(K) + \sum_{i=0}^{9} F(i)\ T(K)^{i-2} \right) \quad (2)$$

where
- B = -1.21507990E+01

| | | | |
|---|---|---|---|
| F(0) = | -8.49922000E+03 | F(5) = | -1.14604540E-08 |
| F(1) = | -7.42318650E+03 | F(6) = | +2.17012890E-11 |
| F(2) = | +9.61635147E+01 | F(7) = | -3.61025800E-15 |
| F(3) = | +2.49176460E-02 | F(8) = | +3.85045190E-18 |
| F(4) = | -1.31601190E-05 | F(9) = | -1.43170000E-21 |

Equation (2) is valid for a temperature range of 0 to 100 degrees C.

In 1976 Wexler published a revision to the original saturation vapor pressure equation'. Equation 15 from the revision, equation (3) below, can be used to calculate saturation vapor pressure Psat (Pascals) at temperature T(K) (degrees Kelvin IPTS-68). Pamb(Pa), Pdew(Pa), or Pwet(Pa) can be determined by substituting Tamb(K), Tdew(K), or Twet(K) for T(K) in equation (3):

$$(3) \quad Psat(Pa) = \exp\left[F(7) \ln T(K) + \sum_{i=0}^{6} F(i)\, T(K)^{i-2}\right]$$

where
F(0) = -0.2991272900E+04 F(4) = +0.1783830100E-04
F(1) = -0.6017012800E+04 F(5) = -0.8415041700E-09
F(2) = +0.1887643854E+02 F(6) = +0.4441254300E-12
F(3) = -0.2835472100E-01 F(7) = +0.2858487000E+01

Equation (3) is valid for a temperature range of 0 to 100 degrees Celsius.

In 1977 Wexler published a third equation that can be used to determine the saturation vapor pressure of ice'. Equation 54 from this reference, equation (4) below, determines saturation vapor pressure Psat (Pascals) at temperature T(K) (degrees Kelvin IPTS-68). Pwet(Pa) or Pice(Pa) is determined by substituting Twet(K) or Tice(K) for T(K) in equation (4):

$$(4) \quad Psat(Pa) = \exp\left[F(5) \ln T(K) + \sum_{j=0}^{4} F(j)\, T(K)^{j-1}\right]$$

where
F(0) = -0.58653696E+04 F(3) = -0.34031775E-04
F(1) = +0.22241033E+02 F(4) = +0.26967687E-07
F(2) = +0.13749042E-01 F(5) = +0.69186510E+00

Equation (4) is valid for temperatures less than or equal to the triple point of water, 0.1 degrees Celsius.

Equations (1)-(4) determine saturation vapor pressure of pure water or ice (without air). The saturation vapor pressure of water in air differs from the vapor pressure of pure water or ice by small amounts: about 1/2 percent at atmospheric temperature and pressure. A correction, the enhancement factor, can be applied to correct saturation vapor pressure for the effect of air--although Mr Saburo Hasegawa of the U.S. National Bureau of Standards has stated that the magnitude of this correction is usually much smaller than other sources of error in humidity measurement.'

Hyland developed equations that can be used to determine the enhancement factor'. Because these equations are difficult to use for computation, Buck developed simpler equations based on Hyland's

data'*. These equations are described below for water, equation (5), and ice, equation (6). Equations (5) and (6) determine the enhancement factor of water, Fw5, or ice, Fi5, from temperature T(K), degrees Kelvin, and barometric pressure Pbaro(Pa), Pascals. Because Buck's original equations are based on Celsius temperature and millibar pressure units, coefficients B, C, and E have been modified for use with Kelvin temperature and Pascal pressure units. The equation for the enhancement factor of liquid water is given by:

$$(5) \quad Fw5 = 1 + A + Pbaro(Pa)\,[B + C\,[\,T(K) - 273.15 + D + E\,Pbaro(Pa)\,]^2\,]$$

where A = 4.1E-04
B = 3.48E-08
C = 7.4E-12
D = 30.6
E = -3.8E-04

Equation (5) is valid for a temperature range of -20 to 50 degrees Celsius.

The equation for the enhancement factor of ice is given by:

$$(6) \quad Fi5 = 1 + A + Pbaro(Pa)\,[B + C\,[\,T(K) - 273.15 + D + E\,Pbaro(Pa)\,]^2\,]$$

where A = 4.8E-04
B = 3.47E-08
C = 5.9E-12
D = 23.8
E = -3.1E-04

Equation (6) is valid for a temperature range of -60 to 0 degrees Celsius.

To apply the enhancement factor, one simply multiplies the uncorrected saturation vapor pressure by the enhancement factor to determine the corrected value as illustrated in equation (7) below for water and equation (8) for ice:

$$(7) \quad \begin{aligned} Pamb(corrected) &= Fw5\ Pamb(uncorrected), \quad 50\ C \geq T \geq -20\ C \\ Pdew(corrected) &= Fw5\ Pdew(uncorrected) \\ Pwet(corrected) &= Fw5\ Pwet(uncorrected) \end{aligned}$$

$$(8) \quad Pice(corrected) = Fi5\ Pice(uncorrected), \quad 0\ C \geq T \geq -60\ C$$

Equations (7) and (8) are valid for any consistent set of pressure units.

MVEL has not applied an enhancement factor correction to any

humidity measurement before 1983.

Partial pressure of water vapor. Saturation vapor pressure values are used to determine the partial pressure of water vapor Pv. If dew-point or ice-point temperatures are measured, the partial pressure of water vapor is defined to equal the saturation vapor pressure, corrected for enhancement factor, at the dew-point or ice-point temperature--equations (9) and (10) below:

(9) $Pv = Pdew$ or

(10) $Pv = Pice$

If a wet-bulb psychrometer is used to measure humidity, several psychrometric equations are available for calculating the partial pressure of water vapor Pv. Equation (11) is based on a thermodynamic model of wet-bulb behavior:

$$(11) \quad Pv = Pwet - \frac{[Pbaro - Pwet]\,[Tamb(F) - Twet(F)]}{2831 - 1.43\,Twet(F)}$$

Pressure can have any consistent set of units in equation (11).

Equation (11) is included here because it is in fairly common use and has been used by several automobile manufacturers for emission testing. In addition, equations similar to (11) have been used to prepare several published psychrometric charts. The author does not feel qualified to make a statement about the merits of equation (11); however, it is important to point out that there is poor correlation between results calculated using equation (11) and results calculated from the equations used at MVEL.

Although a thermodynamic model of wet-bulb behavior has been used to prepare many psychrometric charts, it has been stated that classical thermodynamics does not provide a completely satisfactory description of a wet-bulb system[1] [2] [3] [4]. Several empirical equations have been developed which may be preferable to equation (11) because they are based on experimental results. Equations (12) and (13) are equivalent forms of Ferrels equation[4] [5] [6] [7] that can be used to determine the partial pressure of water vapor. Equation (12) determines Pv from ambient and wet-bulb temperature (degrees Fahrenheit) and has been used at MVEL to determine humidity for light duty vehicle testing to 1983. Equation (13) determines Pv from temperature measured in degrees Kelvin and has been used at MVEL to determine humidity for heavy duty engine testing.

(12) Pv = Pwet - [Tamb(F) - Twet(F)]

.000367 Pbaro [Twet(F) + 1539] / 1571

(13) Pv = Pwet - [Tamb(K) - Twet(K)]

.000660 Pbaro [1 + .00115 [Twet(K) - 273.15]]

Equation (14), developed at the Japan Meteorology Agency, is similar in form to Ferrels equation, and appears to be superior for Assmann psychrometers of the type used by the Japan Meteorology Agency''.

(14) Pv = Pwet - [Tamb(K) - Twet(K)]

.000700 Pbaro [1 - .00560 [Twet(K) - 273.15]]

Any consistent set of pressure units may be used in equations (12)-(14).

Relative and specific humidity. Equation (15) is used to determine percent relative humidity R,

(15) R = 100 Pv / Pamb

for any consistent set of pressure units.

The specific humidity H (grains of water per pound of dry air) is used to correct oxides of nitrogen emission measurements for the effect of humidity. Equation (16) is used for light duty vehicle testing:

(16) H = 4347.8 Pv / [Pbaro - Pv]

for any consistent set of pressure units. In the Federal Register, equation (16) is sometimes combined with equation (15) and written as:

(17) H = 43.478 R Pamb / [Pbaro - R Pamb / 100] .

It can be seen that equations (16) and (17) are equivalent. Equation (16) is preferable because it is simpler and more fundamental than (17).

Equation (18) is an alternative representation of equation (16) that calculates specific humidity in units of grams of water per kilogram of dry air:

(18) H = .0006211 Pv / [Pbaro - Pv]

A slightly different version of equation (16) has been used internally at MVEL to investigate humidity calculation procedures. The constant 4347.8 can be expressed more accurately as

$$(19)\quad \frac{18.01534 \text{ (kg/mole water)}}{28.967 \text{ (kg/mole air)}} (7000 \text{ grains/lb}) = 4353.484$$

Equation (20) has been published in internal documentation at MVEL investigating humidity calculation procedures, but it has not been used for official certification or fuel economy testing.

$$(20)\quad H = 4353.484\ Pv / [Pbaro - Pv]$$

for any consistent set of pressure units.

A third constant has been used for heavy duty engine testing for model years 1979-1983. The constant in the specific humidity equation can be expressed as

$$(21)\quad \frac{18.01534 \text{ (kg/mole water)}}{28.9645 \text{ (kg/mole air)}} = .62198 = .62200$$

This value has been used to calculate specific humidity in units of grams of water per gram of dry air--equation (22) below:

$$(22)\quad H = .622\ Pv / [Pbaro - Pv]$$

The same heavy duty test procedure calculates specific humidity in units of grains of water per pound of dry air by converting the constant in equations (21) and (22):

$$(23)\quad H = [453.59 \text{ gm/lb} / .0648 \text{ gm/gr}]\ .622\ Pv / [Pbaro - Pv]$$

$$= 4353.904\ Pv / [Pbaro - Pv]$$

A third value, the water vapor volume concentration Y, is calculated from equation (22) to determine Pv / [Pbaro - Pv]--equation (24)

$$(24)\quad Y = [28.9645 / 18.01534]\ .622\ Pv / [Pbaro - Pv]$$

$$= 1.000032\ Pv / [Pbaro - Pv]$$

For model years 1984 and later, the equation used to calculate specific humidity for heavy duty engine testing is the same as light duty, namely, equations (16)-(18).

If a user wishes to use the most accurate specific humidity equation available, equations (25) and (26) can be used:

$$(25)\quad \frac{18.01534 \text{ (kg/mole water)}}{28.9645 \text{ (kg/mole air)}} (7000 \text{ grains/lb}) = 4353.86$$

$$(26)\quad H = 4353.86\ Pv / [Pbaro - Pv]$$

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Humidity measurement below freezing. Although MVEL does not presently test manufacturer emission and fuel economy vehicles at temperatures below freezing, equations in this article can be used at low temperatures.

At temperatures below 0°C, relative humidity should be determined with respect to water, that is, Pamb should be determined with respect to the saturation vapor pressure of liquid water at the ambient temperature[4,11]. If temperature is below freezing and saturation vapor pressure equation (1), (2), or (3) (for water) is used, it is necessary to extrapolate below 0°C.

To determine Pv, one can use a dew-point hygrometer or a wet-bulb psychrometer. For dew-point hygrometers, it is necessary to determine whether the hygrometer measures ice-point temperature, in which case equations (4) and (6) can be used, or whether the hygrometer measures the dew-point temperature of supercooled water. Equations (1)-(3) can be extrapolated for supercooled water, and used with equation (5).

If a photoelectric detector is used to maintain a mirror at the dew point or frost point for temperatures below 0°C, the saturation vapor pressure equation for ice should probably be used. For photoelectric control, Wexler states "There can be little question of whether the liquid or solid phase is involved, for supercooled liquid will not long last under such conditions without changing to ice".[11]

If a wet-bulb psychrometer is used, Ferrels equation is valid below 0°C and can be used.[4] If the wet bulb wick is covered with ice, the Pwet term in equation (12) or (13) should be calculated with respect to ice.[4] As mentioned above, however, the Pamb term would still be calculated with respect to water. If a bare bulb is covered with ice, special corrections may be required that are not described here[4].

Caution is required for any attempt to measure humidity at low temperatures with a wet-bulb psychrometer. Wexler states "At temperatures below freezing, the psychrometer continues to function, but the magnitude of the depression is greatly reduced and proper precautions must be taken to obtain reliable data."[11] For temperatures below freezing, dew-point hygrometers appear to have greater than ordinary advantages versus the wet-bulb psychrometer.

Summary. This article describes several procedures for calculating humidity that have been of interest to MVEL, either because they have been used for vehicle emission testing, or because they may be useful in the future. Equations (4), (6), and (14) have not been used at MVEL in the past and there are presently (1983) no plans to use them for certification or fuel economy testing. Nevertheless, these equations are included here because they appear to be the best equations currently available for testing under important conditions: cold temperature or with Assmann psychrometers.

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Information about these equations may be important in the future.

Readers should not assume that humidity calculation procedures in use elsewhere are unacceptable for emission or fuel economy testing simply because they are not described here. Many high quality equations are described in the literature, especially for the calculation of saturation vapor pressure. Most saturation vapor pressure equations agree very closely with the ones presented here.

On the other hand, readers should carefully evaluate any psychrometric equation used to calculate the partial pressure of water vapor from ambient and wet-bulb temperature. Wide variation exists between results produced by different psychrometric equations and a choice of incompatible psychrometric equations can easily cause correlation problems.

Appendix A contains a summary of the humidity equations used by MVEL for vehicle emission and fuel economy testing at different times in history.

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| | Light Duty Vehicle And Truck | | Heavy Duty Engine | | | Humidity Evaluation | | |
|---|---|---|---|---|---|---|---|---|
| | to 1983[1] | 1983+[1] | to 1978[1] | 1979-1983[1] | 1984+[2] | to 1983[1] | 1983+[1] (water) | 1983+[1] (ice) |
| Saturation Vapor Pressure | (1) | (3) | (1) | (2) | (3) | (1) | (3) | (4) |
| Enhancement Factor | None | (5) | None | None | (5) | None | (5) | (6) |
| Psychrometric Equation | (12) | (13)[3] | (12) | (13) | (13)[3] | (13) | (13) | (13) |
| Specific Humidity | (17) | (16) | (17) | (22) (23) | (16) | (20) | (16) (26) | (16) (26) |
| Relative Humidity | (15) | (15) | (15) | (15) | (15) | (15) | (15) | (15) |
| Water Vapor Volume Concentration | None | None | None | (24) | None | None | None | None |

Numbers in parenthesis refer to equations in the body of the Technical Report.

1. Revised light duty humidity calculation procedures were implemented April 4, 1983.
2. Model year.
3. Psychrometric equation not required for dew-point hygrometers.